

Prospect of Rapidity Asymmetry and Nuclear Modifications

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Abstract. In asymmetric heavy ion collisions like dA or pA , particle production yields are different in the forward (d - or p -side) and backward (A -side) rapidity directions. The rapidity distribution reflects the geometry and phase-space distribution of nuclear matter. These properties may depend on the time evolution of the collision. Due to the smallness of the backward-forward differences, the rapidity asymmetry factor can be useful to quantify nuclear modification effects, like e.g. shadowing and the EMC effect. Our work is a survey of the nuclear modification factor and the rapidity asymmetries at RHIC energies. We analyze the rapidity dependence and the strength of the nuclear effects. We focus on the high transverse momentum region, and make predictions for the role of nuclear modifications and rapidity asymmetries for future experimental measurements at increasing absolute values of rapidity.

Keywords: pQCD, intrinsic k_T , pion production, Cronin effect

PACS: 24.85.+p, 13.85.Ni, 13.85.Qk

1. Introduction

Measuring nuclear modifications is not only interesting by itself, but is crucial to the understanding of the hard-probe signature of the quark-gluon plasma (QGP) formed in high energy heavy ion collisions. The modifications can be determined experimentally by different methods in a wide kinematical region: (i) the nuclear modification factor, $R_{AA'}^h(p_T)$ can magnify the deviation caused by collective nuclear effects relative to 'simple' nucleon-nucleon collisions; (ii) the (pseudo)rapidity asymmetry, $Y_{Asym}^h(p_T)$, measures differences of the hadron spectra between back-

ward and forward directions. The deviation from unity of the above two quantities originates in the geometrical and nuclear properties of the colliding system.

Measuring $R_{AA'}^h(p_T)$ and $Y_{Asym}^h(p_T)$ was an important task for past and present experimental collaborations [1, 2], and is going to remain at the center of attention of future experiments. In this paper we would like to emphasize the connection between the two quantities and present recent results [3, 4, 5] for upgraded detectors at RHIC and future experiments at the LHC.

2. Quantifying Modifications in the Nuclear Medium

The nuclear modification measures the effect of the collective nuclear forces in a pA or AA' collision, compared to an average nucleon-nucleon collision. The deviation can be measured as a ratio of the given hadron (h) spectra per nucleon in AA' to the NN collisions. The nuclear modification factor can be defined for any given pseudorapidity:

$$R_{dA}^h(p_T, \eta) = \frac{1}{\langle N_{bin} \rangle} \cdot \frac{E_h d^3 \sigma_{dA}^h / d^3 p_T}{E_h d^3 \sigma_{pp}^h / d^3 p_T} \Big|_{\eta}. \quad (1)$$

Nuclear effects can make $R_{dA}^h(p_T, \eta)$ greater or smaller than 1, representing an enhancement or suppression, respectively, relative to the NN hadron spectra.

In asymmetric collisions, hadron production at forward rapidities may be different from what is obtained at backward rapidities. It is thus of interest to study ratios of particle yields between a given pseudorapidity value and its negative in these collisions. The pseudorapidity asymmetry $Y_{Asym}(p_T)$ is defined for a hadron species h as

$$Y_{Asym}^h(p_T) = E_h \frac{d^3 \sigma_{AB}^h}{d^3 p_T} \Big|_{\eta < 0} \Big/ E_h \frac{d^3 \sigma_{AB}^h}{d^3 p_T} \Big|_{\eta > 0}. \quad (2)$$

Let us consider the ratio of the backward and forward nuclear modification factors in dAu collisions for species h :

$$\begin{aligned} R_{\eta}^h(p_T) &= \frac{R_{dAu}^h(p_T, \eta < 0)}{R_{dAu}^h(p_T, \eta > 0)} = \\ &= \frac{\langle N_{bin}^{\eta > 0} \rangle}{\langle N_{bin}^{\eta < 0} \rangle} \cdot \frac{E_h d^3 \sigma_{dAu}^h / d^3 p_T|_{\eta < 0}}{E_h d^3 \sigma_{pp}^h / d^3 p_T|_{\eta < 0}} \Big/ \frac{E_h d^3 \sigma_{dAu}^h / d^3 p_T|_{\eta > 0}}{E_h d^3 \sigma_{pp}^h / d^3 p_T|_{\eta > 0}}, \end{aligned} \quad (3)$$

where $\langle N_{bin} \rangle$ is the average number of binary collisions in the various impact-parameter bins, and it is given by the thickness function of the Glauber model. Therefore, $\langle N_{bin}^{\eta > 0} \rangle = \langle N_{bin}^{\eta < 0} \rangle$. Furthermore, the pp rapidity distribution is symmetric around $y = 0$. Thus, if the same backward and forward (pseudo)rapidity ranges are taken in both directions (i.e. $|\eta_{min}| \leq |\eta| \leq |\eta_{max}|$), then the pp yields cancel in eq. (3) and one obtains that the ratio defined in eq. (3) is identical to the

pseudorapidity asymmetry eq. (2):

$$Y_{Asym}^h(p_T) = R_\eta^h(p_T) = \frac{R_{dAu}^h(p_T, \eta < 0)}{R_{dAu}^h(p_T, \eta > 0)} . \quad (4)$$

3. Nuclear Modification at Forward and Backward Rapidities

We analyzed several types of shadowing parameterizations such as HKN [6], FGS [7], EKS [8], HIJING [9], and the most recent EPS08 [10]. We choose the two latter parameterizations, which are characterized by the largest nuclear effects. Both have strong suppression at lower x , where we augmented HIJING with multiple scattering corresponding to the saturated Cronin model with $C = 0.35$ (GeV/c)² as in Refs. [11, 12]. The EPS08 is based on the earlier EKS, however the authors included not only eA data, but the latest results from the RHIC dAu experiment [13]. Inclusion of the RHIC data results in strong suppression at small x values. In parallel a large anti-shadowing appears at around $x \approx 0.2$, due to the normalization.

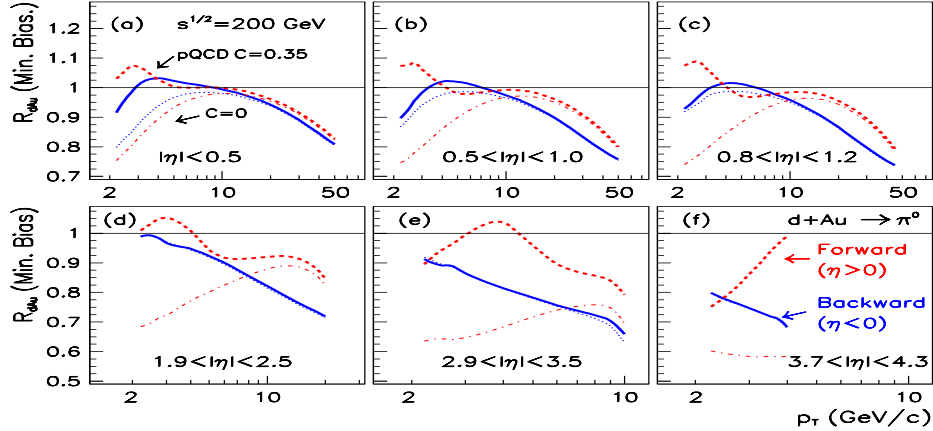


Fig. 1. (Color online.) Nuclear modifications to the forward and backward direction based on HIJING [9] shadowing parameterization. (See text for details.)

Applying these shadowing parameterizations we calculated $R_{dAu}^h(p_T, \eta)$ in wide ranges of η from backward to forward. Results are presented on Fig. 1 for HIJING. Forward and backward calculations are plotted with (red) dashed and (blue) solid respectively. We also plotted using thin dotted and dash-dotted lines on Fig. 1 HIJING calculations for $R_{dAu}^h(p_T, \eta)$ without multiple scattering indicated by ' $C = 0$ '. The differences on Fig. 1 between the pQCD calculations with and without multiple scattering diverge between $\eta > 0$ and $\eta < 0$. In the backward direction the lack of scattering centers in the d nucleus limits the possible collisions, thus the two curves merge as η increases. In the forward direction, without multiple scattering

HIJING gives a suppression at small p_T related to low x values. The deviation is growing as η increases. Note the lack of experimental data in the backward direction. The opening with increasing $|\eta|$ between the curves without and with multiple scattering suggests an η -dependent multiple scattering similarly to Ref. [14].

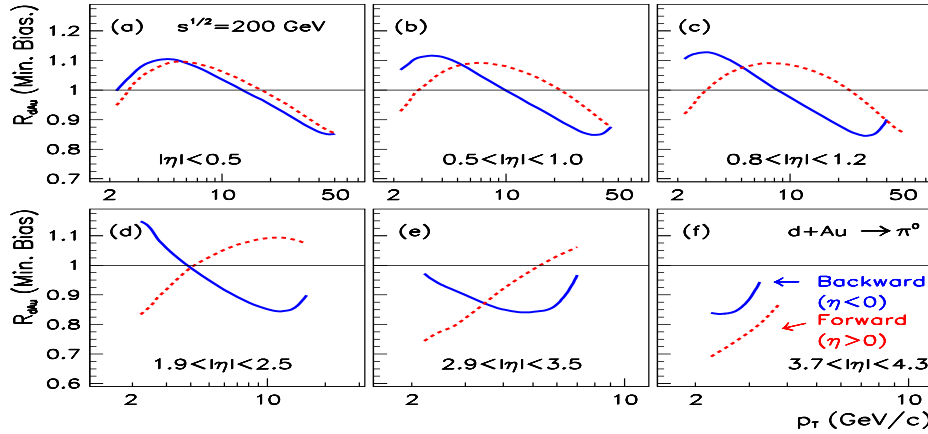


Fig. 2. (Color online.) Nuclear modifications to the forward and backward direction based on EPS08 [10] shadowing parameterization. (See text for details.)

On Fig. 2 we calculated the $R_{dAu}^h(p_T, \eta)$ applying the EPS08 shadowing parameterizations. *Solid (blue)* lines represent the backward, *dashed (red)* lines are for the forward calculations. In the EKS/EPS08 frameworks the effect of multiple scattering (Cronin e.g. in Ref. [15]) is modeled with a strong anti-shadowing peak at around $x \approx 0.2$. At small η forward and backward have similar slopes, but at $\eta \gtrsim 1.5 - 2.0$ this trend flips over due to reaching the steep positive slope from the new low- p_T RHIC dAu data. High η and low p_T data are fitted well with EPS08, but at high p_T the anti-shadowing peak overestimates the data around midrapidity [16].

4. Analyzing Rapidity Asymmetry Data

Fig. 3 shows the calculated rapidity asymmetry, $Y_{Asym}^h(p_T)$ in the same negative/positive η ranges previously presented for $R_{dAu}^h(p_T, \eta)$. Based on eq. (4) this is the ratio of the nuclear modification factors in the proper backward and forward rapidity ranges. Since STAR [2] has published data on pseudorapidity asymmetry, this gives a nice opportunity to compare different models with measured values reflecting the nuclear modifications in the backward direction. EPS08, plotted with

(blue) dashed lines, agrees well with the data in a wide p_T range. HIJING itself (dotted red curves) shows a similar trend, but inclusion of multiple scattering with $C = 0.35$ (GeV/c)² turns over the slope below $p_T \lesssim 4 - 5$ GeV/c at higher η (solid red lines). Similarly to the $R_{dAu}^h(p_T, \eta)$ studies in Sec. 3, this suggests that the efficiency of multiple scattering should decrease going beyond midrapidity.

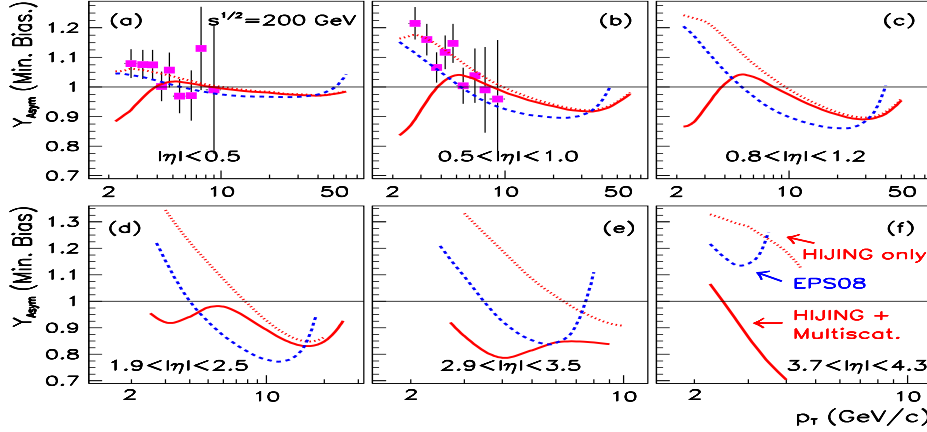


Fig. 3. (Color online.) Rapidity asymmetry calculated with HIJING [9] and EPS08 [10] shadowing parameterizations. (See [2] for data and text for details.)

5. Conclusions

We analyzed the nuclear modification factor, $R_{dAu}^h(p_T, \eta)$ and the (pseudo)rapidity asymmetry, $Y_{Asym}^h(p_T)$ in a wide rapidity range. We showed that these physical properties are related to each other: both reflect the geometry of the collisions and nuclear modifications. We found the equivalence between them in a general formula. This relation led us to test our calculated nuclear modification factors on backward hadron production, which has not been measured directly yet.

Nuclear modifications at midrapidity follow an x scaling in a wide kinematical range as we presented in Refs. [16, 17]. The pQCD improved parton model agrees with experimental data from CERN SPS up to RHIC energies [5, 12]. Several shadowing parameterizations and nuclear PDFs were tested to get the best χ^2 with the experimental data. We found that off-midrapidity the x -scaling is violated using standard shadowing parameterizations.

To correct this problem, a rapidity dependent multiple scattering would be desirable, which is related to the path length (number of scattering centers) of a particle in the system. This would be equivalent to a strongly b -dependent inhomogeneous shadowing parameterization.

Acknowledgments

Discussions with Dieter Röhrich [BRAHMS] and Jamie Dunlop [STAR] are thankfully acknowledged. Our work was supported in part by Hungarian OTKA PD73596, T047050, NK62044, and IN71374, by the U.S. Department of Energy under grant U.S. DOE DE-FG02-86ER40251.

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